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Computational Geometry based Remote Networking

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***Abstract*— In recent years wireless sensor networks (WSNs) have become one of the most active research areas due to the bright and interesting future promised to the world of information technology. It is an emerging field which is accomplishing much importance because of its vast contribution in varieties of applications. Coverage is one of the important aspects of WSNs and many approaches are introduced to maximize it. It is the key research issue in WSN as it can be considered as the measure of the Quality of Service (QoS) of sensing function for a sensor network. The goal of coverage is to have each location in the physical space of interest within the sensing range of at least one sensor. By combining computational geometry and graph theoretic techniques, specifically the Voronoi Diagram (VD), Delaunay Triangulation (DT) and Graph Search algorithms, can solve the problem. This paper defines some recent research approaches on coverage of WSNs using VD and DT. Also shows how they are being utilized in various research works.**

***Index Terms*— Coverage, Wireless Sensors Networks (WSNs), Voronoi Diagram (VD), Delaunay Triangulation (DT).**

I. INTRODUCTION

In recent years there has been increasing interest in the field of WSNs. A WSN consists of a number of wireless sensor nodes. These nodes are characterized by being very small in size with limited energy usually supplied by a battery. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks. Sensor networks represent a significant improvement over traditional sensors [4]. Sensor nodes can be placed on predetermined positions or randomly deployed. These networks are typically used to monitor a field of interest to detect movement, temperature changes, precipitation, etc. and very useful for military, environmental, and scientific applications. One of the most active research fields in WSNs is that of coverage. The coverage problem has been studied extensively, especially when combined with connectivity and energy efficiency. Constructing a connected fully covered, and energy efficient sensor network is valuable for real world applications due to the limited resources of sensor nodes. Coverage reflects how well the deployed sensor nodes can monitor a set of targets in surveillance area. The coverage problem is essentially a Quality of Service (QoS) problem which guarantees the monitored area is covered by one or more sensor nodes. VD is a fundamental algorithm for resolving the coverage problems of WSNs. It is a set of discrete sites (points) partitions the plane into a set of convex polygons such that all points inside a polygon are closest to only one site. This construction effectively produces polygons with edges that are equidistant from neighboring sites. The VD allows sensors to distribute the sensing task by partitioning the space in a meaningful way. Coverage can be measured in different ways depending on the application. This paper shows that the coverage problem [1, 2, 3] and some of its variants can be treated in a unified manner using suitable generalizations of the VD and DT.

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II. PRELIMINARIES

A sensor network is consisting of a large number of sensor nodes and the position of sensor nodes need not be engineered or predetermined. Sensor network protocols and algorithms must possess self-organizing capabilities because the node lifetime depends on battery lifetime. This also means that. Instead of sending the raw data to the nodes responsible for the fusion, they use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data.

Coverage is usually interpreted as how well a sensor network will monitor a field of interest. There are various coverage problems including area coverage, k-coverage, m-connected k-coverage problems etc [5]. An *area coverage* problem is to find a minimum number of sensors to work such that each physical point in the area is monitored by at least a working sensor. If each position in the area is monitored by at least k $(k \geq 1)$ active sensors, the sensor network is said to be a k coverage sensor network where k *is* the coverage degree**.** The communication graph of a given set of sensors M is m-connected if for any two vertices in M, there are m vertex-disjoint paths between the two vertices. An *m-connected k-coverage* problem is to find a minimum number of sensors to work such that each physical point in the area is monitored by at least k active sensors and the active sensors form an m-connected graph.

The VD allows sensors to distribute the sensing task by partitioning the space in a meaningful way. The voronoi cell of a sensor s is the subset of the plane in which all points are closer to s than to any other sensors. Let $P=\{p_1, p_2, . . ., p_n\}$ be a set of n distinct points in the Euclidian plane. This are called the *sites*. The voronoi diagram of P is the subdivision of the plane into n cells, one for each site. Therefore partition the plane by assigning every point in the plane to its nearest site. All those points assigned to p_i form the *voronoi region* or *voronoi cell* $V(p_i)$*.* A point q lies in the cell corresponding to a site $p_i \in P$ *iff* Euclidean_Distance (q, p_i) < Euclidean_Distance (q, p_j), for each $p_i \in P, j \neq i$. Note that we have defined this set to be closed. Some points do not have a unique nearest site, *nearest neighbor*. The set of all points that have more than one nearest neighbor form the VD, $V(P)$ [6]. In Fig. 1 p_i is the site points, $V(p_i)$ is a voronoi cell, q is a free point, e is voronoi edge and v is a voronoi edge.

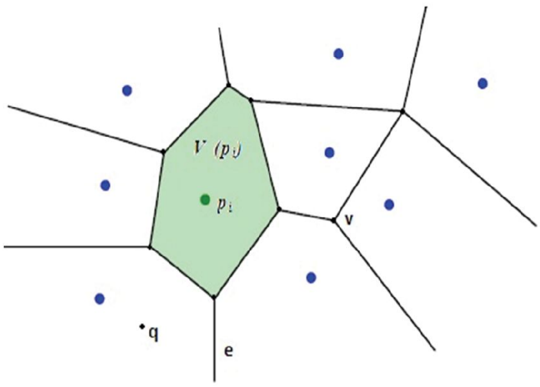
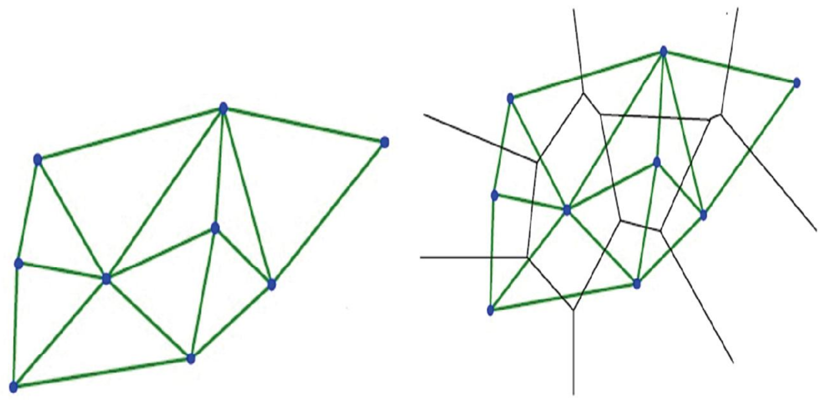


Figure 1.Voronoi Diagram $V(P)$ of $n= 9$ sites

In 1934 Delaunay proved that when the dual graphs is drawn with straight lines, it produces a planar triangulation of the Voronoi sites P (if no four sites are co-circular), now called *Delaunay Triangulation D (P)* [6]. Straight line dual of a VD is Delaunay Triangulation (DT). DT can be used to find the two closest sites by considering the shortest edge in the triangulation. The DT can be obtained by connecting the sites in the Voronoi diagram whose polygons share a common edge. Fig. 2 (a) shows the DT for the VD in Fig. 1, and Fig. 2(b) shows the DT superimposed on the corresponding VD.

III. SOME EXISTING RESEARCH ON COVERAGE PROBLEM IN WSNS USING VORONOI DIAGRAM

This paper defines some research approaches on coverage of wireless sensor networks using voronoi diagram and present in some detail the algorithms, assumptions, and results. This paper defines several terms and concepts and then shows how they are being utilized in various research works.



(a) (b)

Figure 2. (a) Delaunay triangulation *D (P)* for the sites in Fig. 1. (b) Delaunay triangulation and Voronoi diagram: Fig 1 and Fig. 2(a)

A. Worst and Best-case Coverage in Sensor Networks

S. Megerian, F. Koushanfar and M. Potkonjak [1] briefly discussed worst and best-case coverage in sensor networks. By combining computational geometry and graph theoretic techniques, specifically the VD and graph search algorithms, authors established the main highlight of the paper—an optimal polynomial time worst and average case algorithm for coverage calculation for homogeneous isotropic sensors. The DT used to find the two closest sites by considering the shortest edge in the triangulation. They also presented several experimental results and analyze potential applications, such as using best and worst-case coverage information as heuristics to deploy sensors to improve coverage.

Worst-Case Coverage and Maximal Breach Path: A target is *Breach* if it is not monitored by any sensor. In *worst-case coverage* problem Breach is defined as the minimum Euclidean distance from a path to any sensor in a group of sensors. The problem is to identify a *Maximal Breach Path* in an area, connecting the areas initial point and final point. Outline of algorithm for finding *Maximal Breach Path* is as follows:

1. Generate VD for g*iven* sensors.
2. Apply graph theoretic abstraction by transforming VD to a weighted graph.
3. Find *Maximal Breach Path* using binary-search and breadth-first search.

The Maximal Breach Path is not unique. If new sensors can be deployed or existing sensors moved such that this *breach_weight* is decreased, then the worst-case coverage is improved.

Best-Case Coverage and Maximal Support Path: In *best-case coverage* problem *support* is defined as the maximum Euclidean distance from path *P* to the closest sensor in *S*. The problem is to identify a *Maximal Support Path*, P_S, in area *A*, connecting the areas *I* and *F* shows in Fig. 3. Outline of algorithm for finding P_S is as follows:

1. The Voronoi diagram is replaced by the Delaunay triangulation.
2. Each edge in graph *G* is assigned a weight equal to the largest distance from the corresponding line segment in the Delaunay triangulation to the closest sensor.
3. The search parameter *breach_weight* is replaced by the new parameter *support_weight* and the search is conducted in such a way that *support_weight* is minimized.

Figure 3.Sensor field with Delaunay triangulation and a Maximal Support Path (P_S)

The maximal support path may also not be unique. If additional sensors can be deployed or existing sensors moved such that *support_weight* is decreased, then the best-case coverage is improved.
After each additional sensor deployment, the algorithm was repeated to find the new breach region. Over 100 random deployments, breach coverage improved by about 10 percent by deploying just one more sensors. Similarly, the *support_weight* and the midpoint of the corresponding edge in the Delaunay triangulation used as a heuristic for deploying additional sensors to improve support coverage. On average, a 50 percent improvement achieved in support coverage by adding one additional sensor when five nodes have already been randomly deployed.

B. Maximal Breach in Wireless Sensor Networks

A. Duttagupta, A. Bishnu and I. Sengupta proved [2] the lower bound results for maximal breach through its geometric characterization. In 2006 [7] the authors measure the *Maximal Breach Path.* They also formulate the sensor-network design problem as a geometric optimization problem. They have improved polynomial time algorithms for computing the aforesaid measure for a given sensor network. The resulting *breach* is the best that can keep the topology of the starting configuration intact. But later in 2008 [2], the authors have defined a new measure called *average* maximal breach and design an optimal algorithm for it. They have also showed that a relaxed optimization problem for the proposed measure is *NP*-Hard.

C. Blocking Vulnerable Paths of Wireless Sensor Networks

S. Zhou, M. Wu, W. Shu [3] presented the vulnerable paths that rational targets would like to take and block these paths to enhance the network detection performance. The authors focused on reducing the path-based vulnerability to get as much information as possible for any target moving out of the surveillance area. They studied intelligent targets that have the knowledge of existing sensor distribution.
The vulnerability is a measurement of the unawareness of the sensor network when a target is sneaking along some path. A rational target attempts to find a path that is far away from sensors as much as possible which is called the Most Vulnerable Path (MVP). Voronoi Diagram (VD) and Dijkstra’s shortest path algorithm are used as tools to find this path and calculate it vulnerability. The goal of this anti rational target research is to block the most vulnerable paths. They define the problem as:
Given a randomly deployed sensor network,

1. Find the most vulnerable paths that a rational mobile target would take to sneak out of the surveillance area.
2. Find the best locations to place additional sensors, subject to minimize the network vulnerability.

Blocking the Vulnerable Paths depends on the MVP. A specific point needs to be identified as the location of a new sensor called blocking point (BP).The authors proposed four BP selection algorithms, based on two factors. As the Point-based approach, selecting extremes intensity points as BP allows to emphasize on some special areas. Edge-based BP selection first selects a particular edge, and then deploys a new sensor at the center of this edge.
Combine these two factors together, the Four BP selection algorithms are:

1. Best Blocking Effort (BBE): The algorithm select x with maximum $I_c(x)$ in as BP. It is an extreme approach focusing on local maximum.
2. Maximum Side Effect (MSE): On the contrary to BBE, BP is the point x with minimum $I_c(x)$. It is a method that focuses on the global performance.
3. Center of Maximum Exposure Edge (CXE): Among all edges in the MVP, CXE selects the center of e_{xy} with maximum exposure R_{xy} in as BP. Similar to BBE, CXE is also block a path by jam the most exposed edge.
4. Center of Minimum Exposure Edge (CIE): On the contrary to CXE, CIE selects the center of edge e_{xy} withminimum exposure R_{xy} as BP. Putting an additional sensor there can potentially block multiple MVP.

Fig. 4.demonstrates these four approaches, where the plus sign, solid line and bold line represent the existing sensors, original VD edges and original MVP, respectively.
The simulation results have showed a sample distribution of sensors in escaping case, after 10 new sensors are added. BBE putted most new sensors on one direction of the escaping path, and blocked that path thoroughly. CXE is similar to BBE. MSE’s performance is much better, where all new sensors are placed in sparse areas. CIE performed closely to MSE. In the sample of sensor distribution in crossing case, the result was similar to that of escaping case.

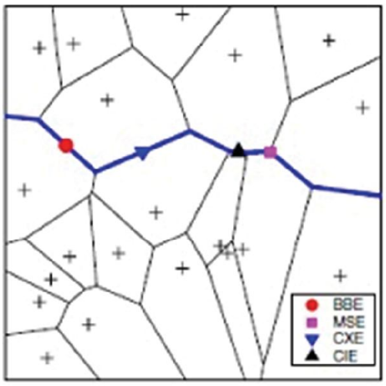


Figure 4.Demonstration of BP selection algorithm

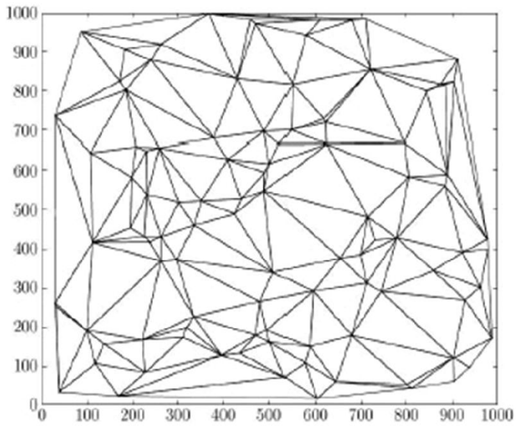
In this work, MSE has the best performance in both cases. It takes care of both current and potential MVP, and deploys sensors on the most needed spots. Minimum extremum based approaches outperform maximum extremum based approaches. The authors have [3] also compared the performance of coverage-based approach with our BP-selection algorithms. Comparison with coverage-based approach further proves the necessity of path-based method for detecting rational mobile targets. It is the first work that concentrates on path-based rational mobile targets detection and sensor network vulnerability.

D. An Efficient Coverage Scheme for Wireless Sensor Network

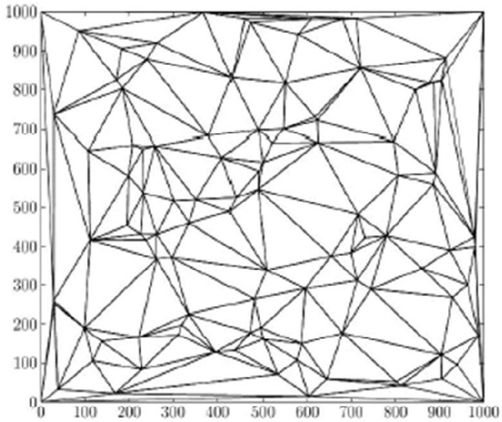
This paper [11] focuses on two coverage strategies namely Delaunay triangulation scheme and Square grid deployment strategy of wireless sensor network.
Here comparative analyses of these two strategies are performed based on different parameters. Theoretical Comparative Analysis and Simulation Based Comparative Analysis of Coverage Strategies have done. Finally it conclude that Delaunay triangulation is more efficient coverage strategy than the square grid deployment because nodes are linked in triangle form and if sensing range of a sensor is increased, then each node can communicate with other node in the network. On the other hand, in square grid deployment strategy if sensing range is increased then overlapping of sensing area is increased which is unexpected for valid data in the coverage of region of interest.

E. Delaunay Triangulation as a New Coverage Measurement Method in Wireless Sensor Network

This paper [8] proposed a new coverage measurement method using DT. In order to show the dense, optimal and scattered areas, it categorizes sensors as ‘fat’, ‘healthy’ or ‘thin’. Where sensors with many close neighbors are known as fat Sensors, Sensors with enough close neighbors are healthy sensors and sensors with few close neighbors are thin sensors. This method also yields the largest empty area of sensors in the field.



(a)



(b)

Figure 5. (a) Delaunay Triangulation (b) Delaunay Triangulation (Corrected)

To use the DT as a WSN coverage measurement tool, the authors add two rules before generating the DT graph. The first rule is to add extra sensors (Fig. 5) at the corners of the field, assumed convex to lead a full triangulation of the field. Secondly, if three sensors are collinear, they move one of them by a random multiple of 0.5 m to let the DT create a triangle.

F. Node Placement for Maximum Coverage Based on Voronoi Diagram Using Genetic Algorithm in Wireless Sensor Networks

The genetic algorithm (GA) is a technique for randomized search and optimization. The authors [12] used GA to determine best places for additional nodes maximizing the coverage. Optimal placement of nodes can guarantee the maximum coverage with less number of nodes and energy consumption decreases. In their network model it is assumed that all sensors are of the same type and deployed randomly in the sensing field. Initially their proposed algorithm uses voronoi diagram to divide the field into cells and then for each cell it uses GA to deploy additional mobile nodes to the holes.

The authors use a 2*n array to represent the solutions in which *i*-th cells are coordination of a node inside a cell. Each co-ordination in each chromosome is random but it must be inside the corresponding voronoi cell. Fitness function is used to determine better solutions that can cover more with less overlap. If there is no overlap between two nodes in a voronoi cell their distance is equal or more than 2r. Selection mechanism is one of the important parts of a GA. They used tournament selection mechanism to select chromosomes for reproducing new generations. In tournament selection each time k individuals are picked randomly and then the chromosome with the best fitness value among them are selected for mating. Selection mechanism is one of the important parts of a genetic algorithm. They used tournament selection mechanism to select chromosomes for reproducing new generations. In tournament selection each time k individuals are picked randomly and then the chromosome with the best fitness value among them are selected for mating. To produce new off springs from the selected parents, they randomly used a one point crossover. The authors select two parents in the population and crossover them. The resulted Childs after crossover are same to their parents because each co-ordination in chromosomes is inside the corresponding voronoi cell. For mutating chromosomes in their proposed genetic algorithm, a new random coordination is calculated inside the voronoi cell and is assigned to a random point in chromosome. Finally, a termination criterion is one of the important parameters in genetic algorithms. There are several methods for specifying termination criterion such as determining a constant number of iterations or until a predefined value for fitness acquired or the fitness value does not change. The authors compared their proposed approach with other works in literature and simulations show that their proposed approach has better performance.

G. Distributed Deployment Strategies for Improved Coverage in a Network of Mobile Sensors with Prioritized Sensing Field

Let S be a set of n distinct weighted nodes (S_1,w_1), (S_2,w_2), . . . , (S_n,w_n) in the plane, where $w_i > 0$ is the weighting factor associated with S_i, for any $i \varepsilon n := \{1,2, . . . ,n\}$. Partition the plane into n regions such that each region contains only one node, which is the nearest node, in the sense of weighted distance, to any point inside that region. The diagram obtained by the partitioning described above is called the *multiplicatively*

weighted Voronoi diagram (MW-Voronoi diagram). This paper [13] proposed efficient deployment strategies for a mobile sensor network, where the coverage priority of different points in the field is specified by a priority function. The multiplicatively weighted Voronoi (MW-Voronoi) diagram is utilized to find the coverage holes of the network for the case where the sensing ranges of different sensors are not the same. In their proposed deployment strategy, the authors considered the following assumptions:

(i) There is no obstacle in the field. Therefore, the sensors can move to any desired location using existing techniques.

(ii) The sensors are capable of localizing themselves with sufficient accuracy in the field.

Under the proposed strategies, each sensor detects coverage holes within its MW-Voronoi region, and then moves in a proper direction to reduce their size. Since the coverage priority of the field is not uniform, the target location of each sensor is determined based on the weights of the vertices or the points inside the corresponding MW-Voronoi region. Their Simulations validate the theoretical results

IV. FUTURE WORKS

In addition there are some more recent works on coverage in WSN using VD. The problem of monitoring targets with hybrid networks is addressed [9], which is composed of some static sensors randomly deployed in the sensing area and some mobile sensors deployed in the edge. Probability model is used to find all the maximal breach paths and ensure that can be detected within the monitoring area. While most existing research efforts in the area of WSNs have focused on Homogeneous nodes, in the paper [10] the authors addressed on X-voronoi to solve the coverage in Heterogeneous networks. It was first study on voronoi for Heterogeneous WSNs.

As future work it can improve in a way that different number of additional nodes is used for each voronoi cell according to its size. Focus on study and comparison of different deployment techniques used in WSN, energy-optimal topology that maximizes network lifetime while ensuring simultaneously full area coverage and sensor connectivity to cluster heads, which are constrained to form a routing technique based on the topology. Influence coverage such as obstacles, environmental conditions, and noise can consider. The integration of multiple types of non-homogeneous sensors in one network platform and the study of the overall coverage of the system also presents several interesting challenges. Investigate methods of optimally deploying multiple sensors at a time. A probability-based exposure can also provide more accurate results. However there are still more work to be done in the field of WSN's coverage so that a global solution can be achieved.

V. CONCLUSION

This paper studies how Voronoi Diagram and Delaunay triangulation is so useful in WSN coverage. Here we have attempted to give an overview of the work that has been done to address the coverage problem in wireless sensor networks. First paper [1] presented best and worst-case formulations for isotropic sensor coverage in wireless ad hoc sensor networks. The second paper [2] study of the geometric and combinatorial properties of single-pair and average maximal breach has led to exact polynomial time algorithms for *computing* the measures. The third [3] paper present a method of decreasing sensor network vulnerability which also points out the path-based network topology study. In the fourth paper [11] a comparative analysis is done between Delaunay triangulation scheme and Square grid deployment strategy. The fifth Paper [8] have proposed a new measurement scheme, based on DT, which gives detailed information about the areas between sensors, distance between them, and fat, healthy and thin sensors. This information can improve understanding sensors of the coverage properties of different coverage promising algorithms, and comparison among them. The sixth paper [12] have proposed a new approach to increase coverage which uses voronoi diagram to divide the field into cells and uses genetic algorithm to find best places to put additional mobile nodes to heal the coverage holes. In the seventh paper [13] efficient sensor deployment algorithms are presented that helps to increase coverage in a mobile sensor network.

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